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# RELIABILITY OF SCHOTTKY AND OHMIC METALLIZATION IN GaAs

Rensselaer Polytechnic Institute

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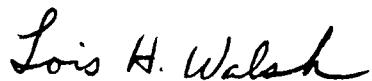


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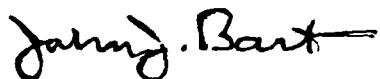
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13. ABSTRACT (Maximum 200 words)  A study was undertaken on the reproducibility and reliability of AuGeNi ohmic contacts (with a barrier layer of Ag) to n-GaAs using a limited number of as available samples. The study showed that there is a large spread in the value of specific contact resistance among the samples and even within each chip or wafer which means that the reproducibility is poor. The contact resistance degrades (increasing by a factor of up to 5) beyond a temperature of 300°C-350°C even for relatively short durations of aging. There is also a significant variation in the aging behavior of different contacts on the chip. Under an electrical stress, the large area contacts are stable at 200°C while the small area contacts show significant degradation in specific contact resistance after about 10 hours of aging. The studies carried out of the reliability of Ti/Pt/Au Schottky contacts on n-GaAs showed that the saturation currents increase by 4 to 5 orders of magnitude beyond a temperature of 300°C-350°C.			
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## EVALUATION

This contract was intended to provide valuable information on the reliability of contacts to GaAs. The objective of this research program was to understand and model ohmic and Schottky contacts and their degradation upon aging. The reproducibility and the dependence of contact resistance on contact size, contact metallurgy, semiconductor sheet resistance and surface concentration in available test structures were evaluated. However, the modeling for the ohmic contact in order to predict the contact resistance as a function of various structural parameter, the process of contact formation and the behavior of the contact with aging was not attempted.

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## Summary

The work described in this report was carried out to evaluate the reproducibility and the reliability of contact resistance in AuGeNi ohmic contacts to n-GaAs in **as available samples**. In the study on the reproducibility in the limited number of samples, it was found that there is a large spread in the values of specific contact resistance ( $\rho_c$ ) among the samples and even within each chip/wafer. In the studies on reliability, the aging behavior of the contacts at high temperatures was examined. These studies revealed that the AuGeNi contacts with a barrier layer of Ag, are stable up to about 300°C, with the  $\rho_c$  varying within only 5 - 10 percent over long periods like 5 - 10 hrs. Beyond these temperatures, the contacts show considerable degradation with the  $\rho_c$  increasing by a factor of 4 to 5 when aging is done at 450°C for short durations like 20 to 40 mins. During the high temperature aging, the large area contacts (area:4500 sq.microns) showed a unique recovery behavior of  $\rho_c$  before undergoing failure. The small area contacts (area:25 sq.microns) however do not show any recovery behavior. It was also found that there is a large variation in the aging behavior of different contacts on the same chip, although their initial  $\rho_c$  values are almost same. When the contacts were aged at 200°C with an electrical stress applied, it was found that the large area contacts are stable for long periods like 50 hrs and more, while the small area contacts show significant degradation with the  $\rho_c$  increasing by almost 100% in about 10 hrs. However, if the initial value of  $\rho_c$  is low in the small area contacts, they do not degrade as rapidly as those having higher values of  $\rho_c$ . This is consistent with the model of joule heating to be largely responsible for contact degradation.

The unique aging behavior of the contacts at high temperatures indicates that complex interactions occur at the interface involving different phases which make high resistance and low resistance contacts to GaAs. The aging behavior with the electrical stress shows that the localized self heating of the contacts due to the current flow is responsible for the observed degradation in  $\rho_c$ .

This work has thus shed new light on the reproducibility and reliability of ohmic contacts used in GaAs MESFETs which play a crucial role in ICs used in variety of defense electronic equipment. It has brought out the following issues which need further investigation:

1. The reproducibility of  $\rho_c$  from sample to sample needs to be improved. The variation in the aging behavior of the contacts on the same chip should be studied in detail.
2. There is a significant degradation of  $\rho_c$  beyond 350°C without electrical stressing and even at 200°C with electrical stress. In view of this, new contact metallurgies/barrier metals should be explored to achieve higher reliability.
3. The present technologies use ion implantation to realize the required sheet resistance of the GaAs below the contact. There is a limit to the carrier concentration achieved by this technique. This calls for new techniques to achieve higher surface concentration. Further, the effective carrier concentration at the ohmic contact / GaAs interface is much less than that predicted by the implant profile. This is due to the "deactivation" of dopants on account of the carrier trapping by the interface states. This phenomenon was first published by Saxena [8] while evaluating ohmic / Schottky contacts on degenerate Si. Similar effects are expected in the case of GaAs and other compound semiconductors.
4. During the aging, the sheet resistance of GaAs below the contact interface undergoes changes which cannot be sensed by the presently available test structures. The six terminal test structure proposed by Linholm, Mazer and Saxena [7] enables an independent measurement of the sheet resistance. This test structure should be incorporated into the MMIC test chip.

Some studies were also carried out on the reliability of Schottky contacts at high temperatures. These indicated that the contacts show significant degradation in V-I characteristics beyond a temperature of 300°C - 350°C, with the saturation current increasing by 4 to 5 orders of magnitude and the ideality factor increasing up to about 3. This indicates that additional interface states are created during the aging.

## Foreword

Although the ohmic contacts to GaAs, specially the AuGeNi contacts, have been studied extensively in the past two decades [1-4], their reliability over a wide range of operating conditions have not been established clearly yet. The metallurgical interactions that take place at the contact interface during the contact formation are fairly well understood through TEM and X-ray analyses; however, the effect of aging on these interactions and its impact on the contact resistance is not clearly understood. In this project, a study was undertaken on the aging behavior of AuGeNi contacts at high temperatures at which the effects of the interactions at the interface are enhanced and hence provide a better insight into the degradation mechanisms. From the observed behavior, processes which might lead to the degradation in  $\rho_c$  were identified.

The reliability of Schottky contacts to GaAs has also been widely investigated. In spite of this, a contact metallurgy which is stable at high temperatures is still not available. TiPtAu is one of the most widely used metallurgy. In this project some studies were made on the reliability of this contact at high temperatures. The effect of aging on the important d.c parameters of the contact was evaluated.

## 1. Introduction

The reliability of AuGeNi ohmic contacts to n-GaAs over a wide range of operating conditions is not clearly established in spite of the extensive studies carried out so far. Very little is reported on the high temperature aging behavior of these contacts. In view of this a systematic study was undertaken on the variation of contact resistance during high temperature aging in available samples. The stability of the contacts at elevated temperatures with an applied electrical stress was also examined. In addition, some studies were also made on the aging behavior of Schottky contacts and MESFETs. The details of the experiments carried out and the results obtained are given below.

## 2. Tasks involved in the project

The following tasks were proposed to be carried out in the project

1. Evaluation of Specific contact resistance ( $\rho_c$ ) of ohmic contacts to n-GaAs in **available samples**
  - reproducibility of  $\rho_c$  from sample to sample.
  - variation of  $\rho_c$  with contact area and surface concentration.
2. Evaluation of effect of accelerated testing (with time, temperature) on  $\rho_c$  with and without electrical stressing.

## 3. Samples

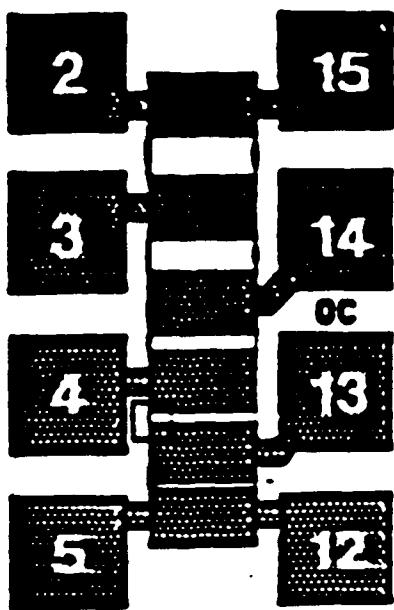
The tasks mentioned above required a large number of samples (for studies on reproducibility) of various types: different semiconductor sheet resistances, different areas and different contact/barrier metallurgies. However, a **very limited number of samples of only two types** were available for the studies. These samples were provided by RADC and GE (Syracuse). Three types of samples were used - 3" wafers, chips and packaged chips. These samples consist of MMIC test structures which include Transmission line (TLM) and Cross bridge (CBKR) structures for contact resistance measurement. The metallurgy of the ohmic contacts in the chips was Au/Ge/Ag/Ni with an overlay of Ti/Pt/Au. The TLM structures had a chain of 6 contacts with spacings of 5, 10, 15, 30 and 40 microns between adjacent contacts. The area of each contact was 4500 sq.micron. The CBKR structures had a chain of 7 contacts. The area of each contact was 25 sq.micron. The test structures are shown in fig. 1. The studies on the Schottky contacts were made on the MESFET structures ( FETFET and Circuit FET structures ) available on the MMIC test chip (fig.2). These contacts had the configuration of Ti/Pt/Au on n-GaAs.

## 4. Specific tasks addressed

In view of the samples made available, the following issues were addressed in the project:

- i. Evaluation of reproducibility of  $\rho_c$  of ohmic contacts to n-GaAs in the available samples.

## TLM STRUCTURE



## CBKR STRUCTURE

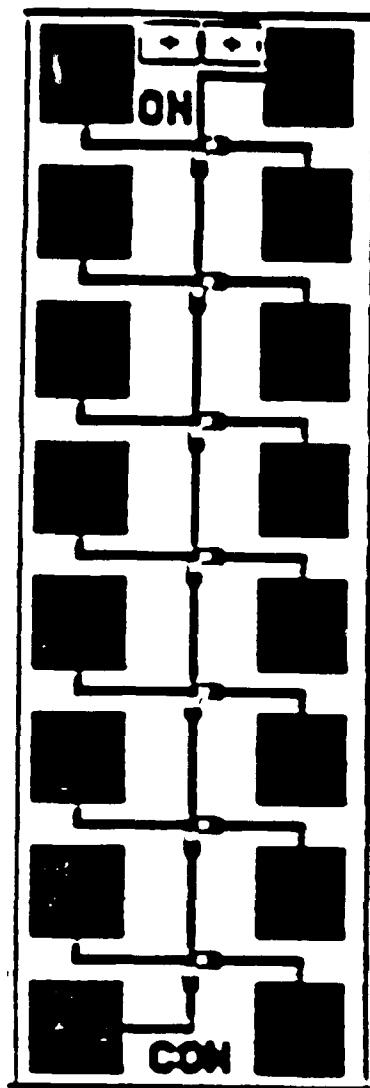
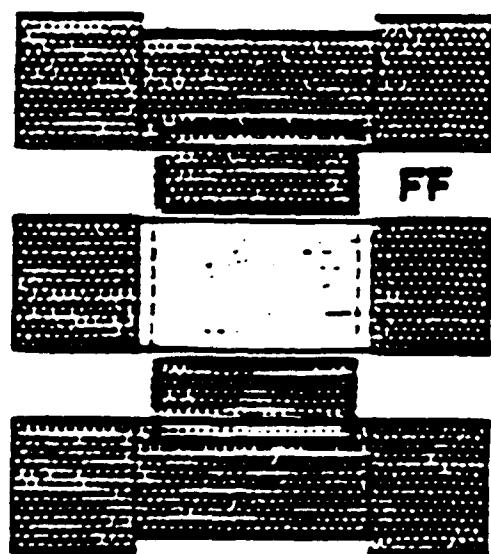


Fig.1 Test structures used for contact resistance measurement in ohmic contacts.

### FATFET



### STD. FET

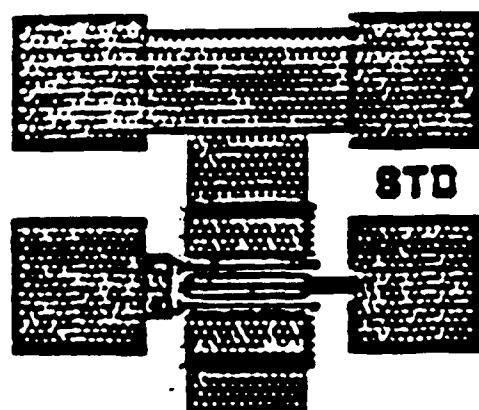


Fig.2 MESFET structures used for studies on Schottky contacts

ii. Evaluation of reliability of  $\rho_c$  of ohmic contacts subjected to aging under different conditions of stressing (temperature, time, current).

## 5. Measurement of contact resistance

### a. Background

The contact resistance is obtained by measurement of resistance in the TLM or CBKR test structures. In the case of CBKR structures, the ratio of the measured voltage to current directly gives the contact resistance ( $r_c$ ). In the case of TLM structures, the ratio of the measured voltage to current gives a resistance value which includes the sheet resistance of the semiconductor channel between any two adjacent contacts. This resistance can be expressed as:

$$r = 2r_c + R_s.(l/w)$$

where  $R_s$  is the sheet resistance of the semiconductor channel between adjacent contacts

$l$  is the length of the semiconductor channel

and  $w$  is the width of the channel

$w$  is also the width of the ohmic contact window.

If  $r_1$  and  $r_2$  are the measured resistances between two pairs of contacts with channel lengths of  $l_1$  and  $l_2$  respectively, then

$$r_1 = 2r_c + R_s.(l_1/w)$$

$$\text{and } r_2 = 2r_c + R_s.(l_2/w)$$

This assumes that all the contacts have the same contact resistance.

From these  $r_c$  can be obtained as:

$$r_c = (r_1 l_2 - r_2 l_1) / (2(l_2 - l_1))$$

It may be noted that this  $r_c$  is the "Front" contact resistance.

In the case of CBKR structures, the  $\rho_c$  is related to  $r_c$  by:

$$\rho_c = r_c \cdot A$$

where  $A$  is the contact area.

In the case of TLM structures,  $\rho_c$  and  $r_c$  are related by:

$$r_c = (R_s \cdot \rho_c)^{1/2} \coth [(R_s / \rho_c)^{1/2} \cdot d]$$

Using these relations, the  $\rho_c$  can be obtained from the measured values of  $r_c$  in both TLM and CBKR structures.

## b. Experimental Work

In the chips provided, the contact resistance was measured in the TLM and CBKR structures. In the case of 3" wafers, the measurements were done on the TLM structures. In the measurement, constant currents of different values (2mA, 5mA and 10mA), of both polarities are passed through the structures and the corresponding voltage drops (across one contact in the case of CBKR structures and between adjacent contacts in the case of TLM structures) are measured. From these, the  $r_c$  and  $\rho_c$  values are obtained.

## 6. Aging experiments

Most of the aging studies reported in the literature are limited to temperatures of 250°C to 300°C. Very little has been reported on the high temperature aging behavior of ohmic contacts. In the present study, the ohmic contacts were aged at high temperatures of up to 650°C and the behavior of  $\rho_c$  was studied. This type of aging is required to understand and model the degradation/reliability mechanisms and understand the roles of the ohmic contact metallurgies and the barrier metals. In addition to the high temperature aging, the contacts were also subjected to aging with applied electrical stress.

### a. Aging without electrical stressing

In this case, the samples were aged in a furnace in a nitrogen atmosphere. Two types of aging were done. In one type, samples were subjected to aging for short durations (ranging from 15 mins to 45 mins) at successively increasing temperatures (ranging from 150°C to 650°C). After each aging step, the contact resistance was measured at room temperature and  $\rho_c$  was calculated. In the second type of aging, the samples were aged at specific temperatures over time intervals of 20 to 60 mins each, up to a total duration of 5 to 10 hrs. In this case also, after each aging step, the contact resistance was measured and  $\rho_c$  calculated.

### b. Aging with electrical stressing

In this case, the packaged samples were aged at elevated temperatures in a temperature controlled oven with specific d.c current flowing through the contacts. With the available setup it was possible to do aging at up to 200°C with electrical stress applied. The accuracy of temperature was  $\pm 1^\circ\text{C}$  and the stability was  $\pm .1^\circ\text{C}$ . The TLM and CBKR structures were aged under constant current stress for durations of 30 to 60 mins up to a total of 10 to 50 hrs. After each aging step, the contact resistance was measured at room temperature and  $\rho_c$  calculated.

## 7. Aging of Schottky contacts at high temperatures

Samples containing MESFET structures were aged at high temperatures, without electrical stress, in the same way as the ohmic contacts. After each aging step, the V-I characteristics of the Schottky contact between the gate and channel were measured. Since packaged chips with Schottky contacts bonded were not available, the aging behavior with electrical stress could not be studied.

## 3. Results

### i. Reproducibility of $\rho_c$ on as fabricated wafers/chips

In the 3" wafers, the measurement of contact resistance was used to generate wafer maps of  $\rho_c$  to show its variation across the wafer area. Typical wafer map is shown in fig. 3. From this it can be seen that there is a variation of 10 to 20 % across the wafer.

In the case of chips, the  $\rho_c$  was obtained from the two TLM and one CBKR structures. The values of  $\rho_c$  obtained for the samples tested are shown in Table-1. The table shows that there is a large spread in the values of  $\rho_c$  from sample to sample and within each sample. Within each sample, the CBKR structures generally gave the lowest value of  $\rho_c$  (lower by typically 2 to 3 times or more as compared to the value given by the TLM structures). Between the samples there is a variation of up to 2 orders of magnitude in the  $\rho_c$  obtained from the TLM structures.

### ii. Reliability of $\rho_c$

#### a. Aging behavior of large area ohmic contacts at high temperatures

Figs.4 and 5 show the typical variations of  $\rho_c$  (obtained from TLM structures) with aging temperature and aging time respectively. These figures show a unique recovery behavior of the contact resistance in both types of aging as described below. This behavior has not yet been reported in the literature.

In the case of aging at different temperatures, the  $\rho_c$  starts to increase at around 250°C to 350°C, reaches a peak at around 400°C to 450°C and subsequently decreases. On further increase in aging temperature,  $\rho_c$  increases beyond the peak value but ultimately drops off to a very low value indicating catastrophic failure of the contact. With increase in the duration of each aging step, the peak in the  $\rho_c$  variation shifts to lower temperatures.

In the case of aging at a specific temperature (isochronal annealing), with increase in aging time, the  $\rho_c$  increases initially, reaches a peak and subsequently decreases. On further aging, the  $\rho_c$  increases again but ultimately drops off to a very low value as in the case of aging at different temperatures. With increase in aging temperature, the peak in the  $\rho_c$  variation occurs at smaller values of aging time.

Thus, in both types of aging, a unique recovery behavior of  $\rho_c$  is observed. A qualitative explanation for this behavior is given below. TEM analyses could not be performed to confirm the validity of this explanation.

Microstructural analyses of the AuGeNi contact interface, reported in the literature [5,6], have shown that it is comprised of Ni<sub>2</sub>GeAs, Au and AuGa phases which are formed during the alloying. In the regions which contain the Ni<sub>2</sub>GeAs, the GaAs layers below the contact get heavily doped by the Ge and hence these show very low contact resistance. The regions with AuGa or Au show very large contact resistance. Thus the  $\rho_c$  of the contact is determined by the extent to which Ni<sub>2</sub>GeAs covers the contact area as compared to AuGa and Au, and the amount of doping of GaAs from Ni<sub>2</sub>GeAs. Further, according to Braslau's model for such inhomogeneous contacts, the  $\rho_c$  is also dependent on the sizes of the columnar conducting regions of the contact.

Previous studies on aging of AuGeNi contacts have shown that the excessive out diffusion

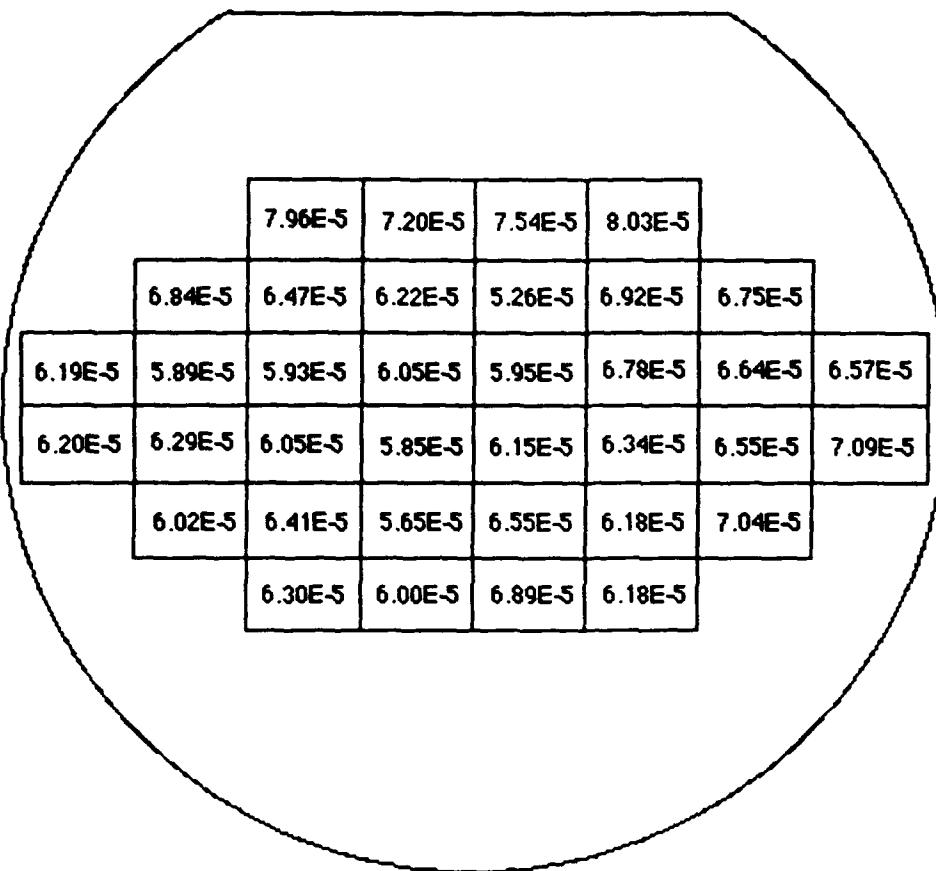


Fig. 3 Wafer map showing the variation of  $\rho_c$  (ohm-sq cm)  
on a 3" wafer

TABLE I: VARIATION OF SPECIFIC CONTACT RESISTANCE AMONG SAMPLES  
SPECIFIC CONTACT RESISTANCE (Ohm-sq.cm)

<u>SAMPLE</u>	<u>TLM-1</u>	<u>TLM-2</u>	<u>CBRR</u>
1	9.3 x 10 <sup>-7</sup>	6.4 x 10 <sup>-7</sup>	1.75 x 10 <sup>-7</sup>
2	2.15 x 10 <sup>-6</sup>	6.15 x 10 <sup>-6</sup>	1.92 x 10 <sup>-7</sup>
3	8.7 x 10 <sup>-7</sup>	5 x 10 <sup>-7</sup>	1.92 x 10 <sup>-7</sup>
4	7.54 x 10 <sup>-7</sup>	1.1 x 10 <sup>-6</sup>	1.63 x 10 <sup>-7</sup>
5	4.72 x 10 <sup>-6</sup>	2.62 x 10 <sup>-6</sup>	2.13 x 10 <sup>-7</sup>
6	8.79 x 10 <sup>-6</sup>	1.79 x 10 <sup>-6</sup>	2.5 x 10 <sup>-7</sup>
7	9.10 x 10 <sup>-7</sup>	9.9 x 10 <sup>-7</sup>	1.45 x 10 <sup>-7</sup>
8	2.49 x 10 <sup>-7</sup>	7.12 x 10 <sup>-8</sup>	2.35 x 10 <sup>-7</sup>
9	3.23 x 10 <sup>-7</sup>	2.54 x 10 <sup>-7</sup>	4.75 x 10 <sup>-7</sup>
10	2.51 x 10 <sup>-5</sup>	2.50 x 10 <sup>-5</sup>	5.32 x 10 <sup>-7</sup>

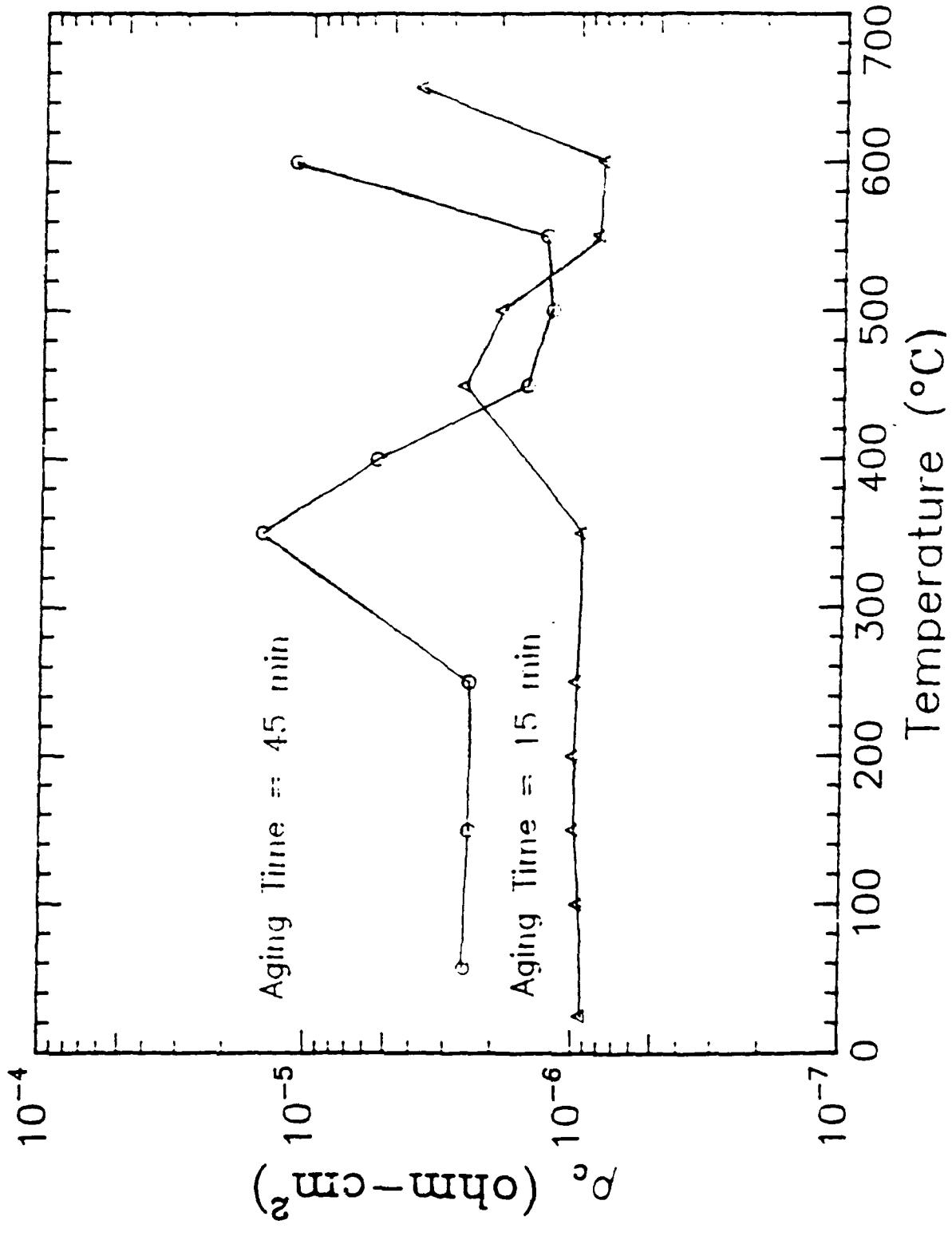


Fig. 1 Variation of  $\rho$ , with aging temperature in large area contacts

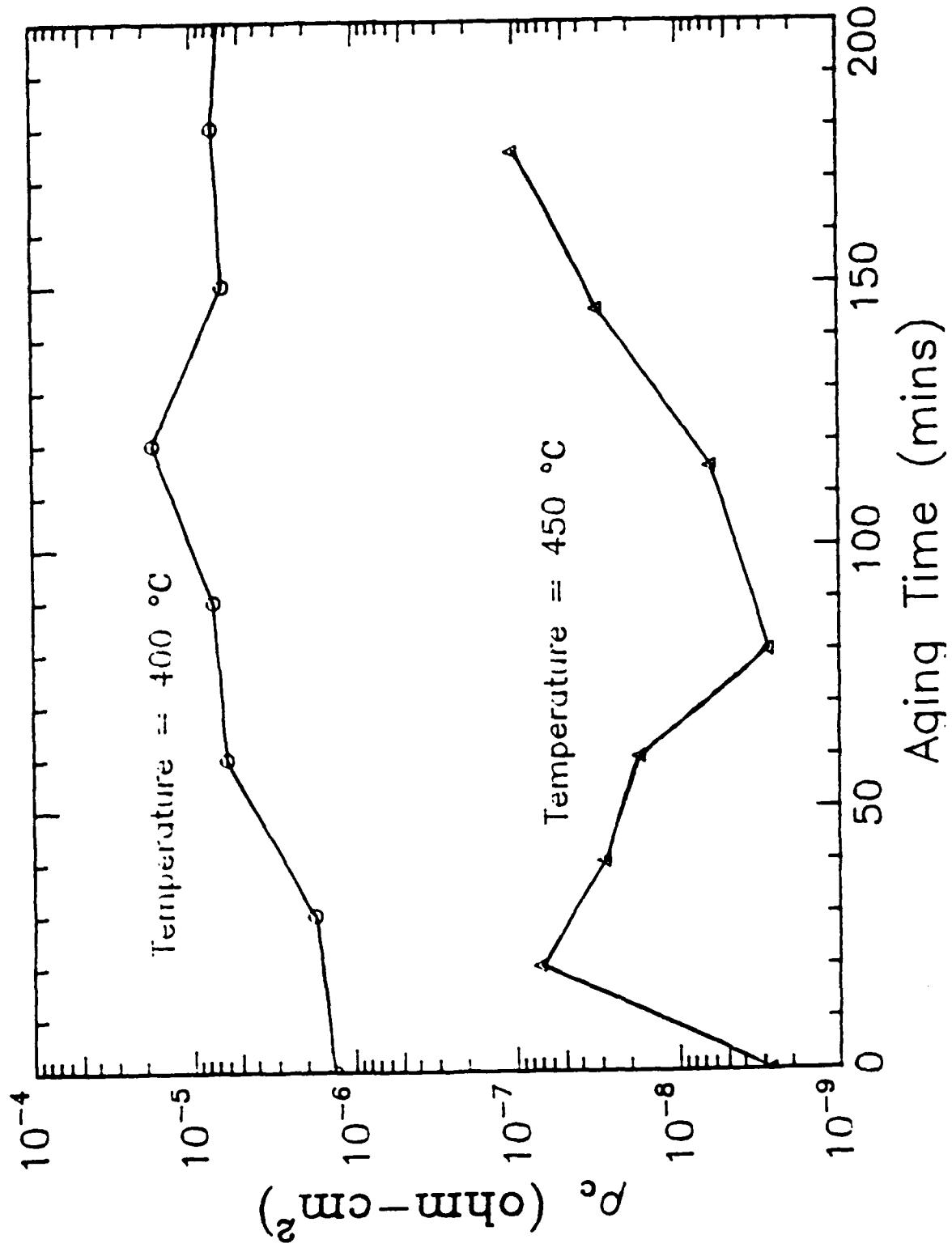


Fig.5 Variation of  $\rho_0$  with aging time in large area contacts.

of Ga and the in diffusion of Au leads to an increase in resistivity of GaAs near the contact interface which leads to an increase in  $\rho_c$ . It has also been reported that when AuGeNi contacts are aged for 10 hrs or more at 400°C there is a tendency for Ni<sub>2</sub>GeAs grains to segregate and for the AuGa phase to show a liquid like flow across the contact area. However, the recovery behavior of the contacts reported here is due to an aggregate of all the processes mentioned above. As the aging progresses, initially (lower temperature or time), the effect of the out diffusion of Ga into Au dominates, giving rise to an increase in  $\rho_c$ ; however at the same time, the grain growth of Ni<sub>2</sub>GeAs and the doping of GaAs by Ge which tend to reduce  $\rho_c$ , also get enhanced. Beyond some point during aging (i.e. a specific temperature or time), the latter effect dominates and hence there is a net decrease in  $\rho_c$ . On further aging, the AuGa tends to dominate the contact area because of its liquid like flow, surpassing the grain growth mechanism of Ni<sub>2</sub>GeAs, thereby leading to an increase in  $\rho_c$ .

In the case of aging at different temperatures, if the duration of each temperature step is increased, all the processes for the mechanisms discussed above get enhanced in each step. Thus the peak in the  $\rho_c$  variation occurs at lower temperatures. Similarly, in the case of aging with time, if the temperature is increased, the changes occurring in each step get enhanced and the peak in the  $\rho_c$  variation is shifted to lower values of time.

#### b. Aging behavior of small area contacts

Figs.6-7 show the observed variations of  $\rho_c$  in CBKR structures with aging time and temperature. The figure shows that the  $\rho_c$  is almost constant at lower temperatures, but starts to increase at around 300 - 350°C. Unlike in the case of large area contacts, no recovery behavior is seen in these contacts. However, the  $\rho_c$  tends to remain fairly constant over a range of temperature or time thereby suggesting that the processes responsible for the recovery of  $\rho_c$  in the case of large area contacts take place in the small area contacts also, but affect the  $\rho_c$  to a lesser extent.

#### b. Variation in aging behavior of contacts

To study the variations in the aging behavior of contacts on the same chip, the  $\rho_c$  of several contacts, in the CBKR structure, was measured after each aging step. Fig.8 shows typical variations of  $\rho_c$  of 4 contacts on a single chip during aging. From the figure, it is clear that there is a large difference in their aging behavior.

#### b. Aging behavior with applied electrical stress

Fig.9 shows the observed variation of  $\rho_c$  with aging time for TLM and CBKR structures aged at 200°C with constant current stress applied during the aging. It can be seen from this figure that the effect of aging on  $\rho_c$  depends upon the current density maintained during the aging. For the same current value, the effect is negligible in large area contacts in TLM structures (contact area: 4500 sq.microns) while it is significant in small area cross bridge structures (contact area: 25 sq.microns) in which the  $\rho_c$  increases by almost 100% after 10 hrs of aging. Further, even in the case of small area contacts, the degradation in  $\rho_c$  with aging depends on the initial value. For a contact with a low initial value, the increase during aging is very small as compared to the one with higher initial value (fig.10). This indicates that a self heating mechanism (due to the power density dissipated,  $I^2.R/Area$ ) is responsible for the observed aging behavior. This is supported by the observation that the large area contacts in the TLM structure in which the power density is low, the degradation in  $\rho_c$  is negligible.

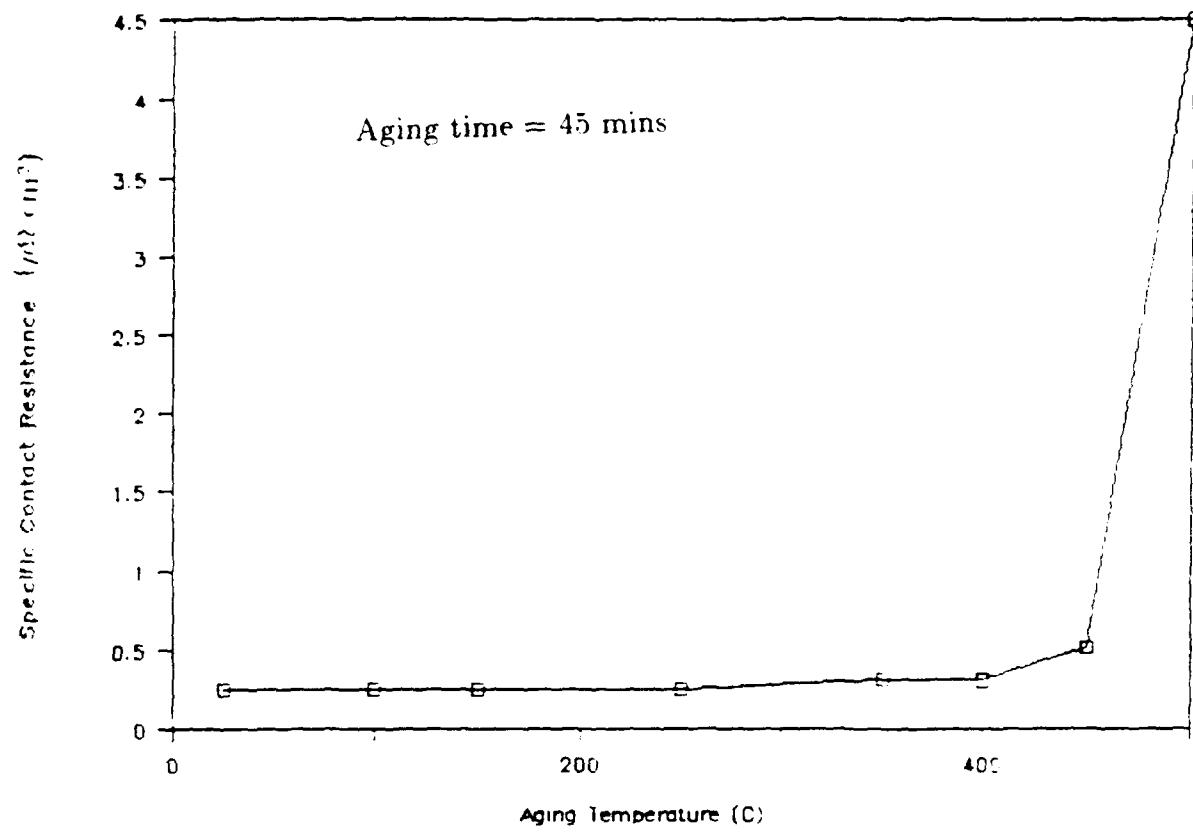


Fig.6 Variation of  $\rho_c$  with aging temperature in small area contacts

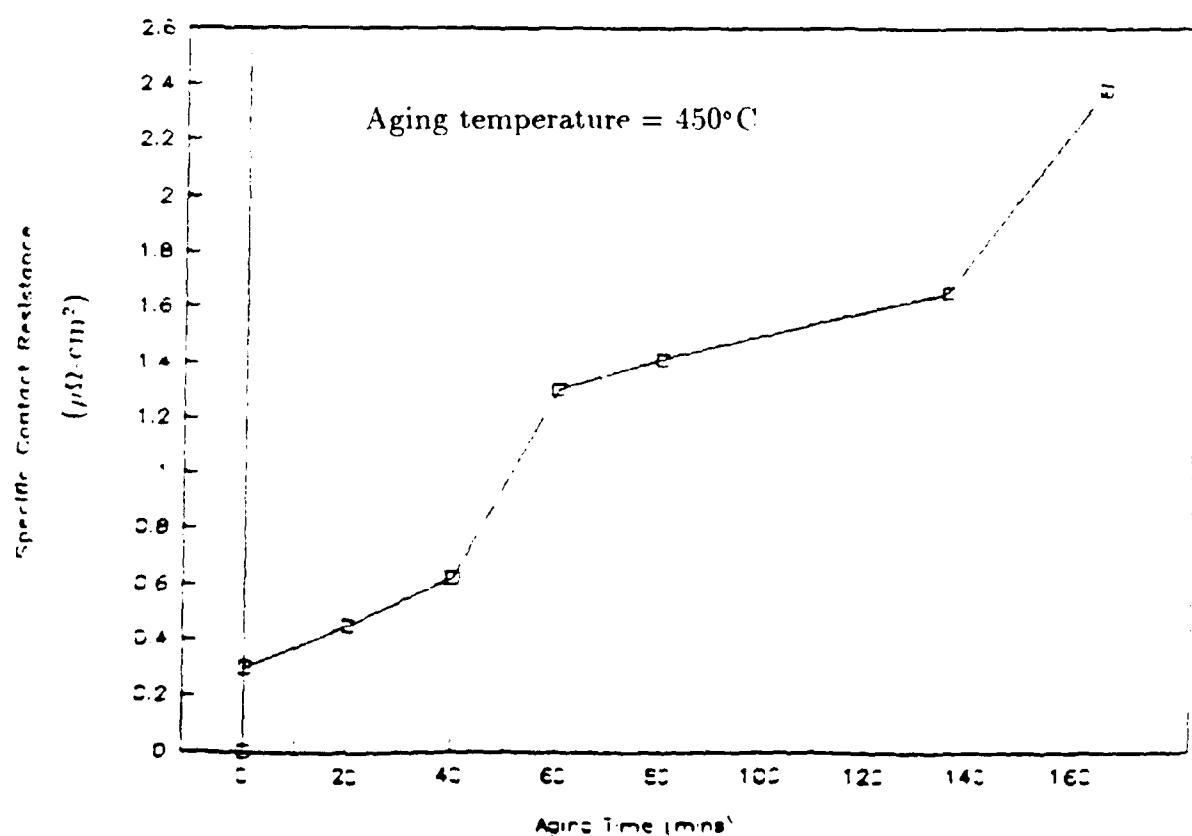


Fig.7 Variation of  $\rho_c$  with aging time in small area contacts

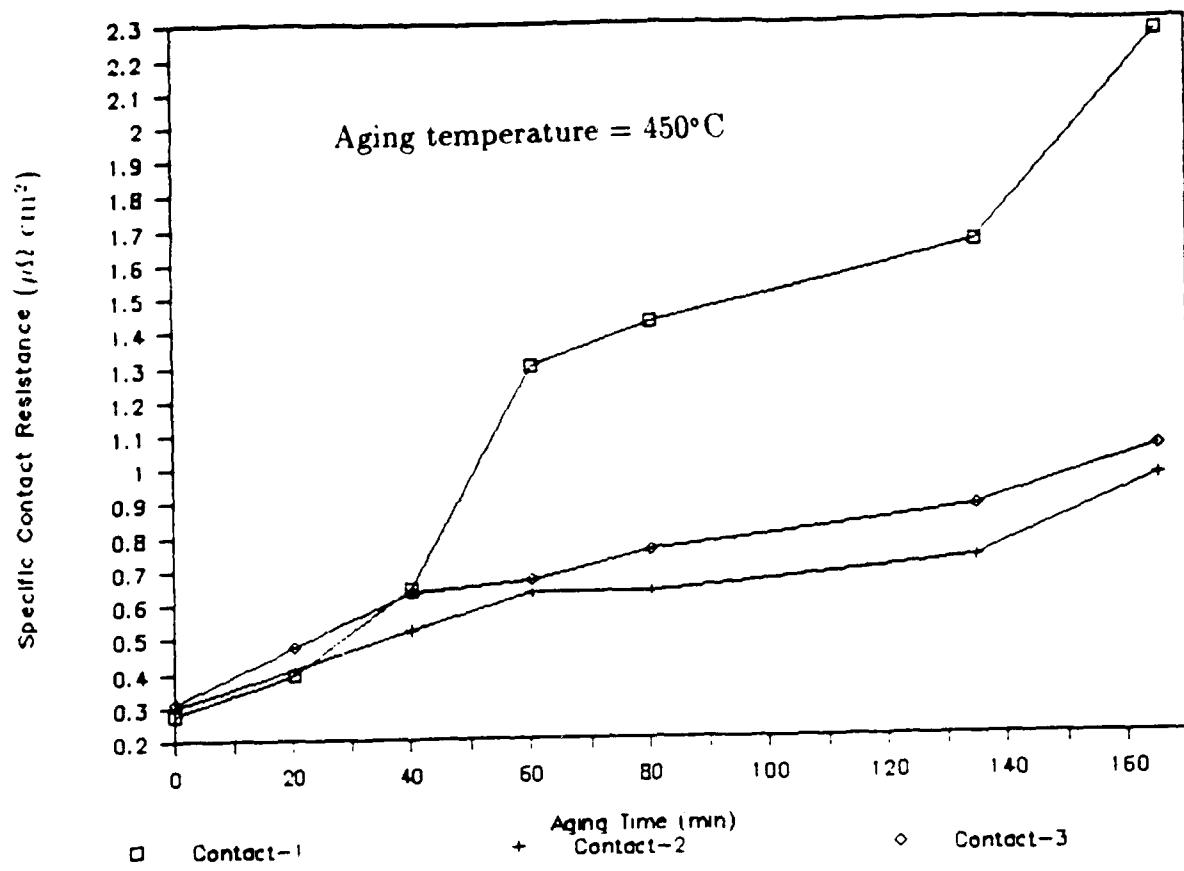


Fig.8 Variation of aging behavior in small area contacts.

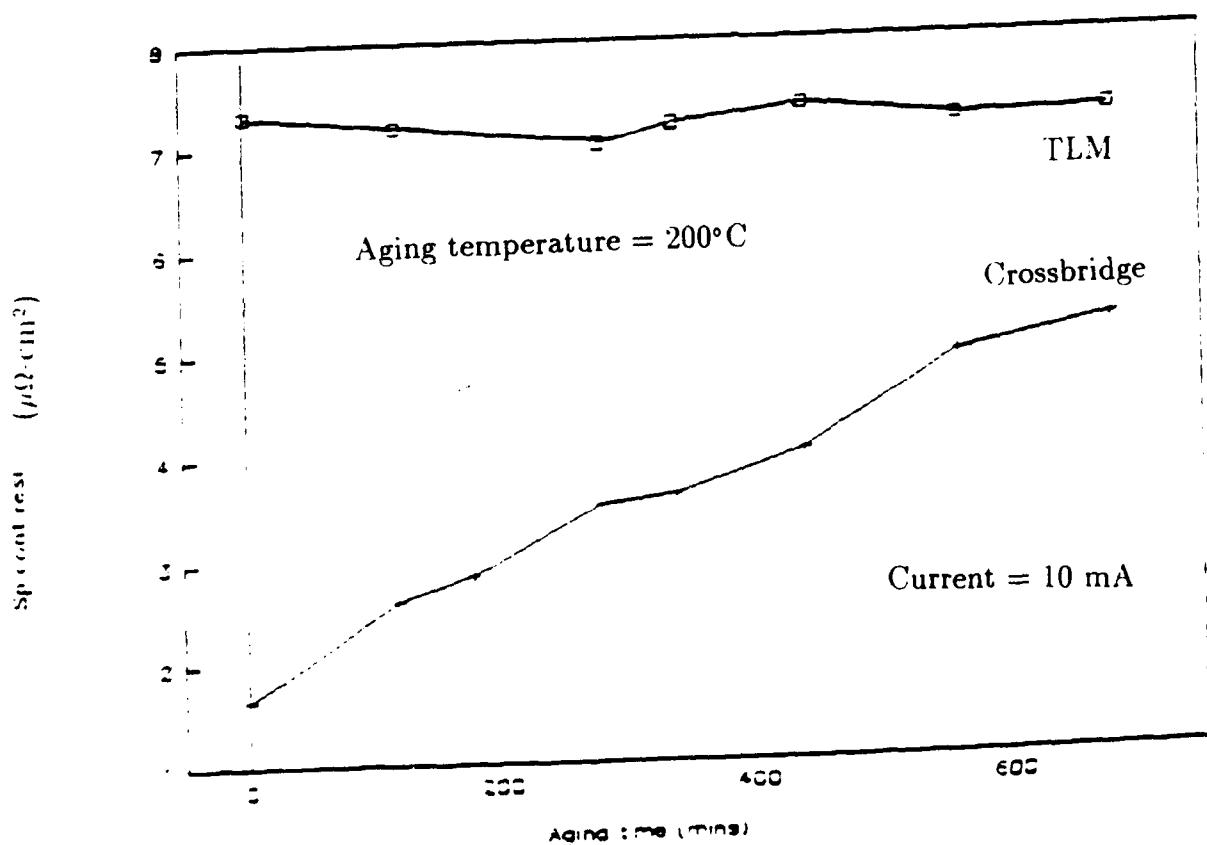


Fig.9 Aging behavior of contacts under electrical stress.

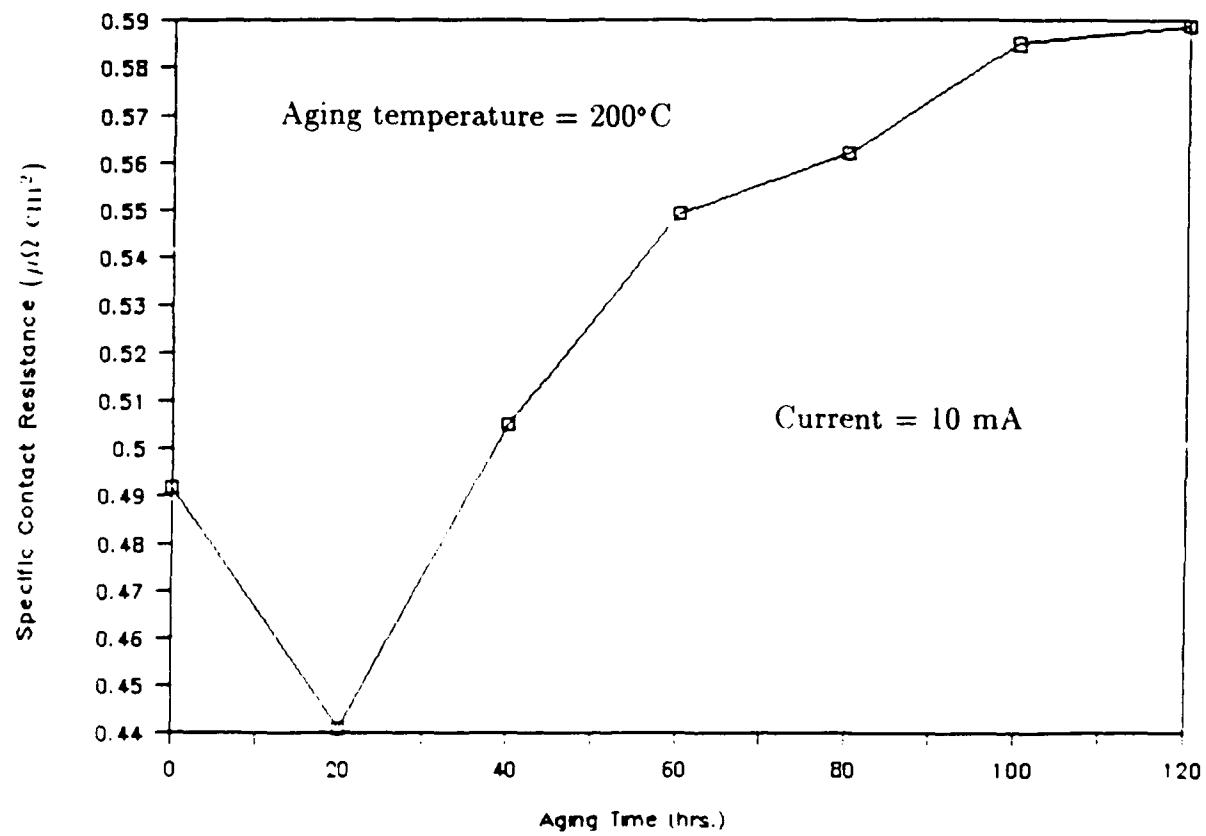


Fig.10 Aging behavior of small area contacts with low initial value of  $\rho_{cr}$ , under applied electrical stress.

### iii. Aging behavior of Schottky contacts

From the measured V-I characteristics of Schottky contacts after each high temperature aging step, the important parameters, viz, the ideality factor ( $n$ ) and the saturation current ( $I_s$ ) were obtained. Typical variations of  $n$  and  $I_s$  with aging temperature and time are shown in figs. 11 and 12. These figures show that the contacts are stable up to about  $250^\circ\text{C}$  to  $300^\circ\text{C}$  beyond which a significant degradation in characteristics is seen. The saturation current increases by 4 to 5 orders of magnitude at temperatures around  $400^\circ\text{C}$  even for short duration aging. The ideality factor increases to about 2 to 2.7 after high temperature aging. This indicates that additional interface states are created during the aging. Further it is found that the degradation in  $n$  and  $I_s$  is more severe in the small area contacts of standard FETs as compared to the large area contacts of EATFETs.

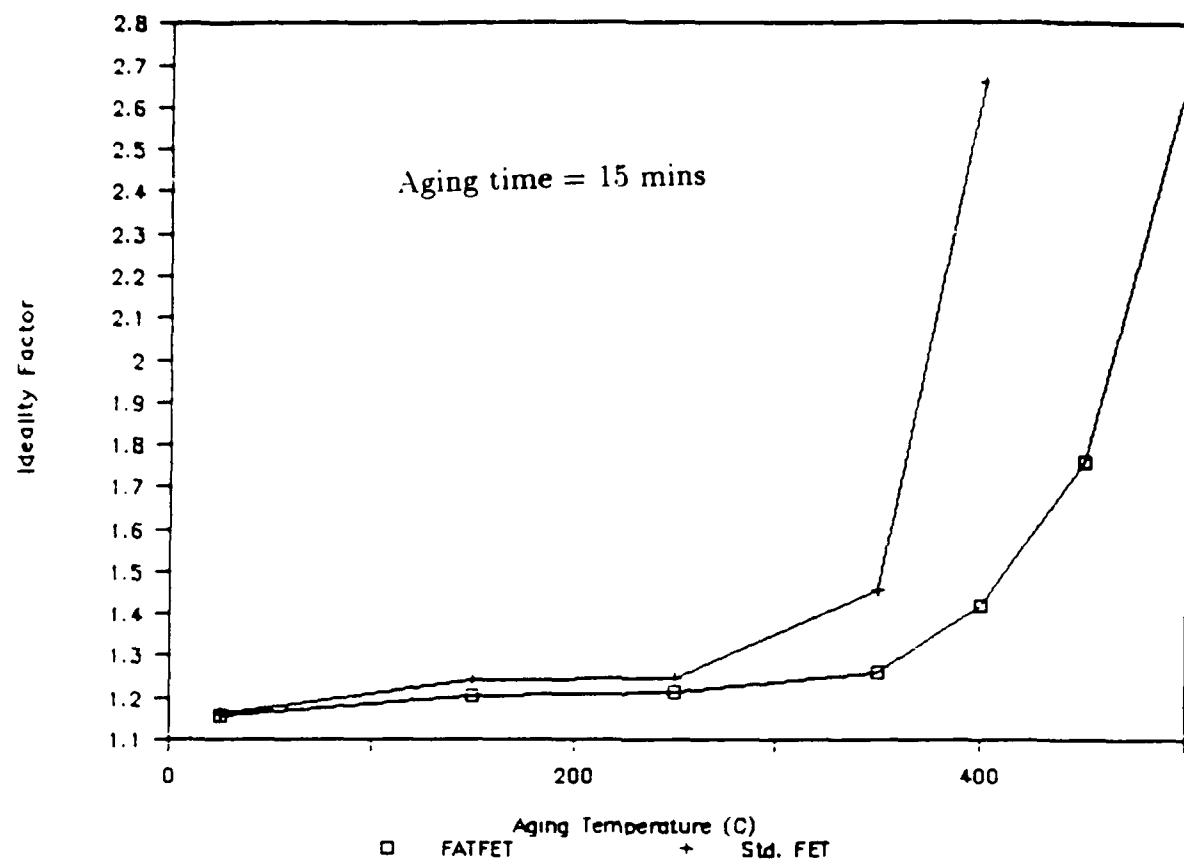


Fig.11(a) Variation of ideality factor with aging temperature in Schottky contacts.

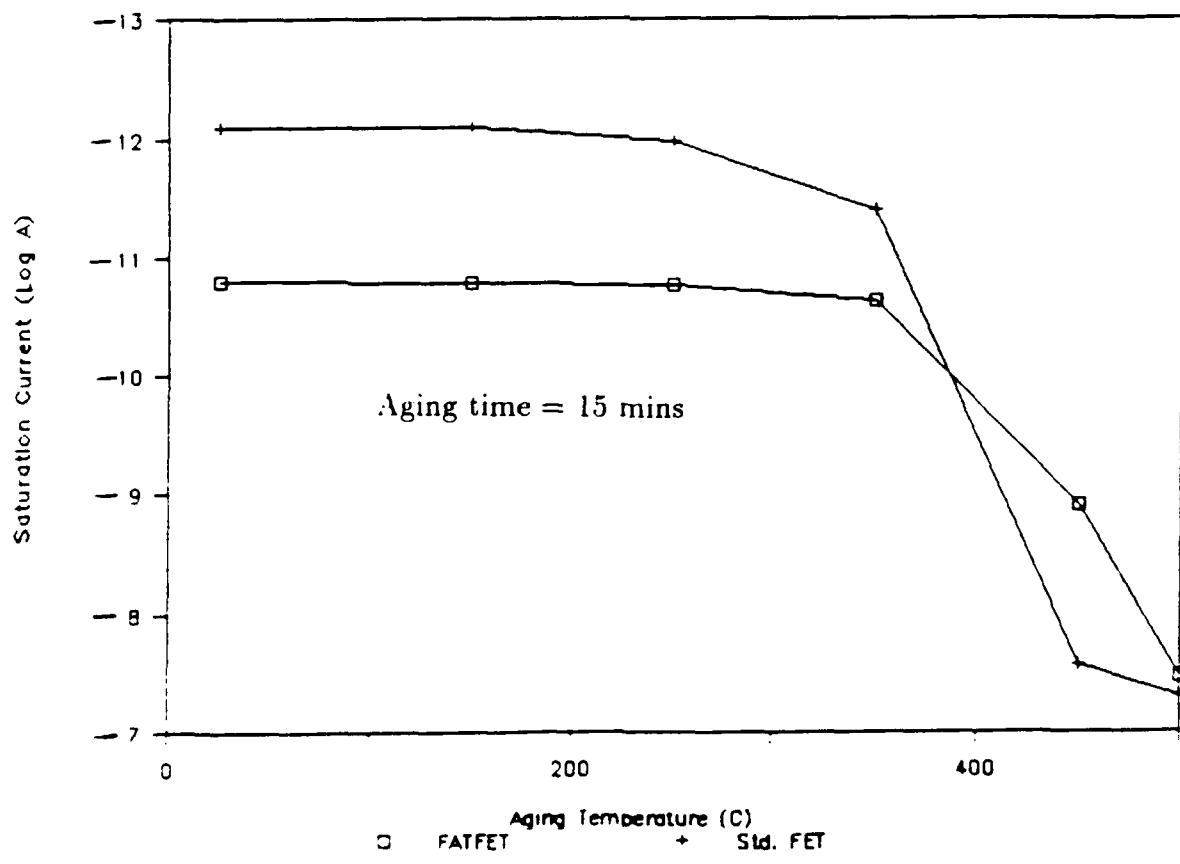


Fig.11(b) Variation of saturation current with aging temperature in Schottky contacts

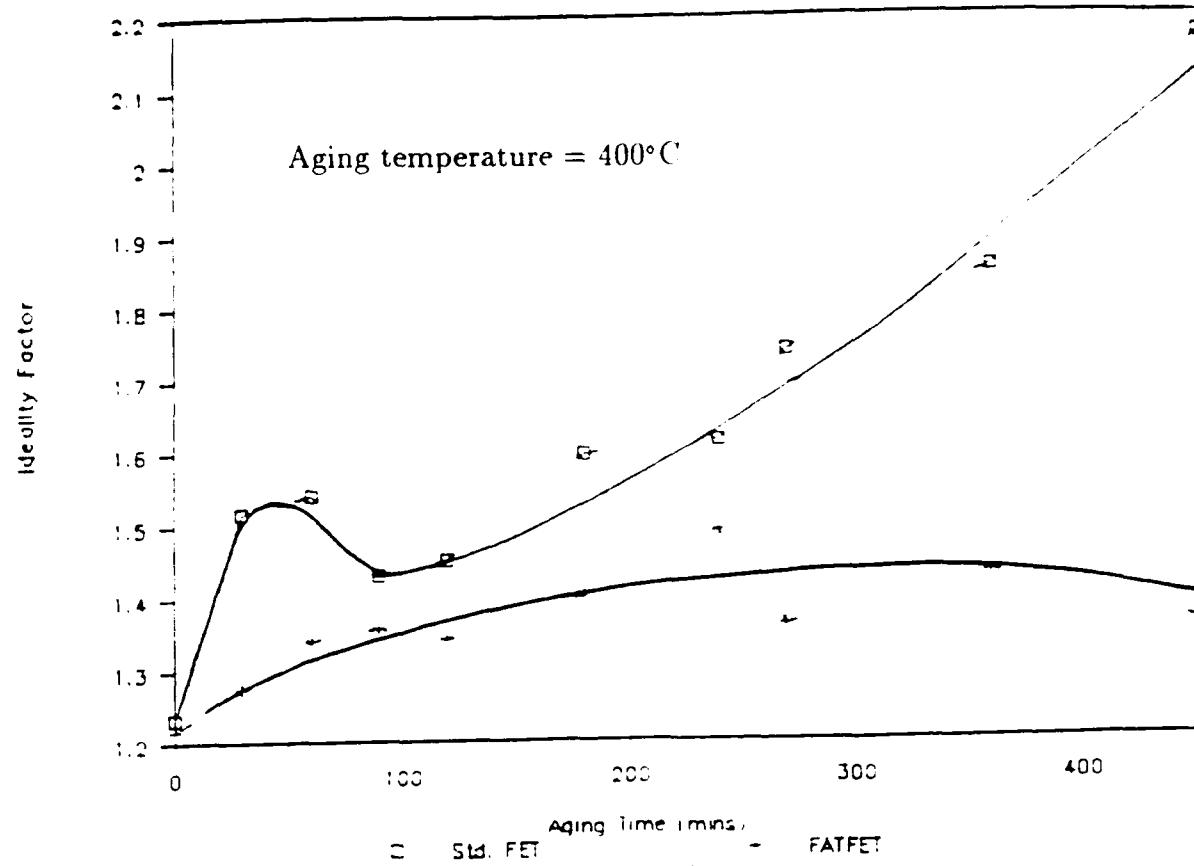


Fig.12(a) Variation of ideality factor with aging time in Schottky contacts

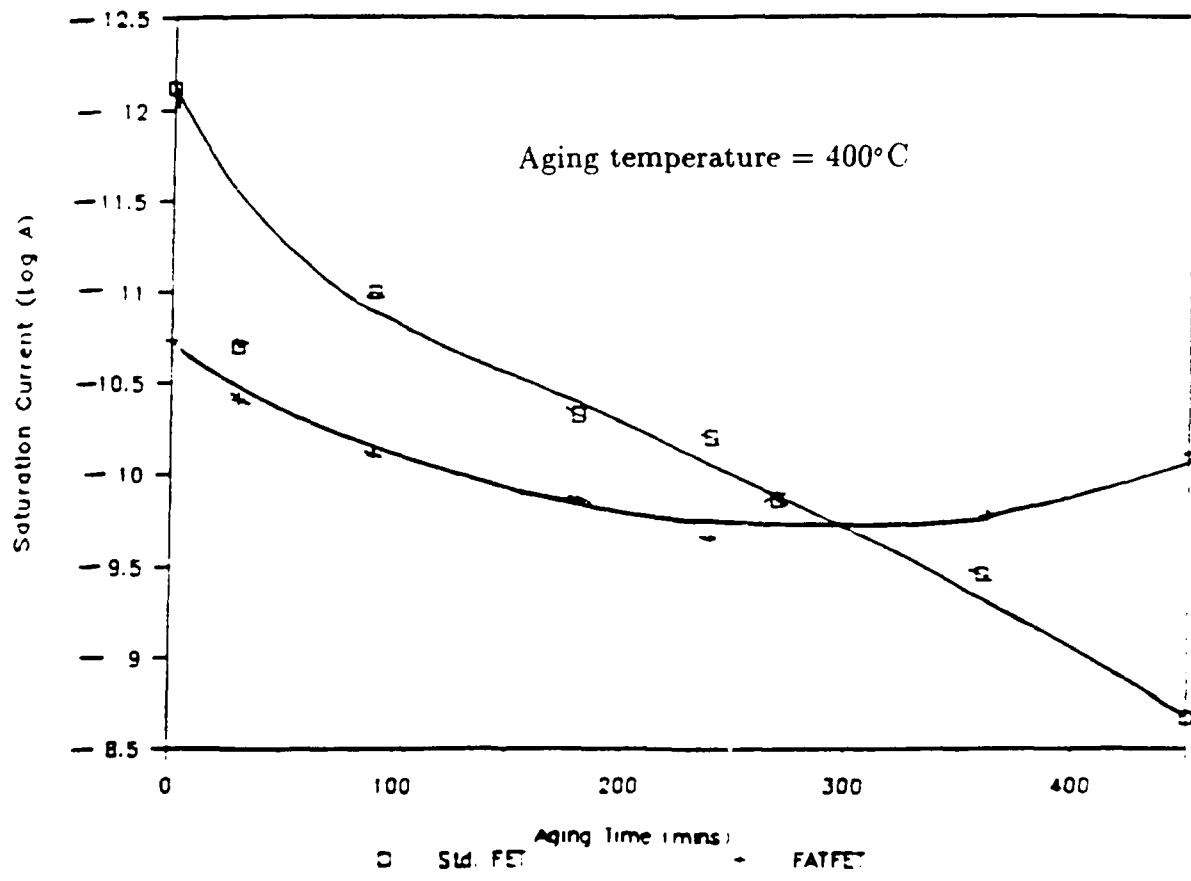


Fig.12(b) Variation of saturation current with aging time in Schottky contacts

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